An X-ray Diffraction Study of Opals

By

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INTRODUCTION

> "In general it (opal) has been characterized as an amorphous mineral gel. In recent years, however, X-ray diffraction studies show that opal is not amorphous but is a submicrocrystalline aggregate of crystallites of cristobolite, containing much non-essential water (Frondel, 1962)".

The purpose of this study was to review the recent literature on opals, to survey by X-ray diffraction the opals in the mineralogy collection at Ohio State University and to report and compare the results of this survey with those previously described.

It is essential to review the literature before discussing the results of my study, not only to provide the reader with some idea of what kind of work has been done in this area, but also to familiarize the reader with the nomenclature of opals. The word opal, like many words in geology, is kind of a basket term for all naturally occurring hydrous amorphous silica and is not specific enough to use in itself. During my discussion of the literature I will discuss a paper from which most of the nomenclature in the literature was taken (Jones and Segnit, 1971). I will also include a discussion of the genesis of opal which is of considerable interest since cristobalite is the high temperature phase of SiO_2, whereas the genesis of opal is thought to occur at low temperatures.

Jones and Segnit subdivide opals into three main groupings: opal-A - the non-crystalline amorphous opals; opal-CT - opals composed of disordered low cristobalite; and opal-C - opals composed of well-ordered low cristobalite. Jones and Segnit state that this material must contain greater than one percent water to be considered an opal. This is an arbitrary criterion, however, the presence of some non-essential water serves to differentiate the well-ordered, opal-C from low cristobalite. This classification of naturally occurring hydrous silica is based strictly on structural considerations although these categories

may be further subdivided on the basis of physical properties. Two broad terms which are based on physical properties are opal, referring to compact and vitreous material, and opaline silica which refers to friable or dispersed material. For instance, within the category of opal-A, diatomite, which is a very friable rock, should be called opaline silica. On the other hand, hyalite, which is a globular, transparent amorphous silica, should be termed opal-A. The following is a summary of these terms:

STRUCTURAL	PHYSICAL APPEARANCE
opal-C (well ordered ∝cristobalite)	opal (compact and vitreous)
opal-CT (disordered ∝cristobalite/ ∝tridymite)	opaline silica (friable or dispersed)
opal-A (highly disordered, nearly amorphous)	

The variety of opals is based on their physical appearance. It is important that these varieties are defined at this point so that we have a common understanding of what is meant when the different varietal names are used. Precious opal is characterized by an internal play of colors which range from red to orange to green to blue. Precious opals may be transparent to milky white translucent material, or in some cases, black. The black opals which display a fire or play of colors are termed black opals. One other varietal name of precious opal is fire opal. Fire opal displays an intense orange to red internal play of colors. The term fire opal has also been used for a transparent red colored opal without a play of colors. This material should be considered common opal.

Common opal is translucent to transparent, milky white, yellow, green, red, or brown, waxy to vitreous material, lacking fire. Wood opal refers to petri-

fied wood in which wood has been replaced by opal. Diatomite is a deposit of the amorphous silica shells of planktonic organisms which accumulate and may be lithified. Diatomite is also known as diatomaceous earth and is usually a white fine grained friable layered rock. Geyserite or siliceous sinter is a light colored, globular to stalactitic, friable opaline silica deposited at or near hot springs or geysers. Hyalite is a colorless, transparent, globular to botryoidal or reniform opal occasionally showing faint tints of blue, green or yellow. Milk opal is translucent to opaque common opal with a milk white color. Moss opal is translucent common opal with dark dendritic inclusions.

According to Hurlbut (1971), opals have a hardness of 5-6 and a specific gravity of 2.0 to 2.25, with a vitreous to waxy luster, and display conchoidal to sub-conchoidal fracture. There are, in fact, many other varietal names. A somewhat exhaustive list with references to the origin of these names may be found in Volume 3, 7th Edition, Dana's System of Mineralogy, Frondel (1962).

Cristobalite is one of the high temperature polymorphs of SiO_2. Cristobalite's stability field is above 1470°C. Why then do we find cristobalite formed at low near surface temperatures? A discussion of the genesis of cristobalite at low temperatures is found in a paper by Jones and Segnit (1972).

Jones and Segnit discuss the metastable formation of low cristobalite and low tridymite at low temperatures. Both cristobalite and tridymite consist of fairly regular six membered rings of silicon oxygen tetrahedra which are linked in sheets and vertically stacked. The sheets are connected by the vertices of the silica tetrahedra. Within the hexagonal layers the orientation of adjacent tetrahedra alternate from pointing up, to the next pointing down, and so on so that no two adjacent tetrahedra point in the same direction. The difference between cristobalite and tridymite is in their vertical stacking. Because of energy considerations at low temperatures, the cristobalitic phase is favored.

Quartz, on the other hand, cannot truly be considered as having layers of tetrahedra. It should be considered a framework structure. ~~Thus,~~ In the nucleation of silica at low temperature with low energy or low ionic mobilities, energy considerations only allow linking of silicon and oxygen in chains. These chains are eventually modified into layers and the hexagonal layer is the most favored structure. The only way for these hexagonal layers to be converted to quartz is by breaking some bonds in order to convert to the framework structure of quartz. At low energies or with low ionic mobility, this conversion from the hexagonal layered pattern to the framework pattern of quartz cannot happen. Therefore, the pattern is simply enlarged, so with low energy or low ionic mobility, the energy requirements of short bond links and low energy rings serve to initiate the growth of silica as tridymite/cristobalite nuclei. Once this nucleation has begun the pattern is merely enlarged and the result is that metastable low cristobalite is formed instead of quartz. For a further discussion of the energy considerations of ring structures of silica tetrahedra, the reader is referred to a paper by Zoltai and Buerger (1960).

The vertical stacking of the cristobalitic layers in this low energy environment is initially very disordered but with limited increase in energy may become more ordered. Thus, there is the possibility of a digenetic grade from opal-CT which represents a disordered low cristobalite to the well-ordered opal-C. Furthermore, it has been reported that amorphous silica opal-A may be diagenetically altered to opal-CT (Pisciotto, 1981).

The diagenesis of amorphous silica is discussed by Pisciotto (1981). He discusses the Miocene age Monterey Shale in California, which is one of the few extensive subaerially exposed units that displays the complete spectrum of siliceous lithologies. Within the Monterey Shale, marine planktonic organisms with siliceous shells were deposited and accumulated on the bottom. As deposi-

tion continued and amorphous silica layers were buried, temperatures increased. Increased temperature caused diagenesis to opal-CT and finally diagenesis to chert. Pisciotto discusses the diagenesis of amorphous silica to opal-CT to chert by means of X-ray diffraction and oxygen isotope analysis. Also discussed is the shift in d spacing of opal-CT with increasing diagenetic grade. The following table was taken from that paper.

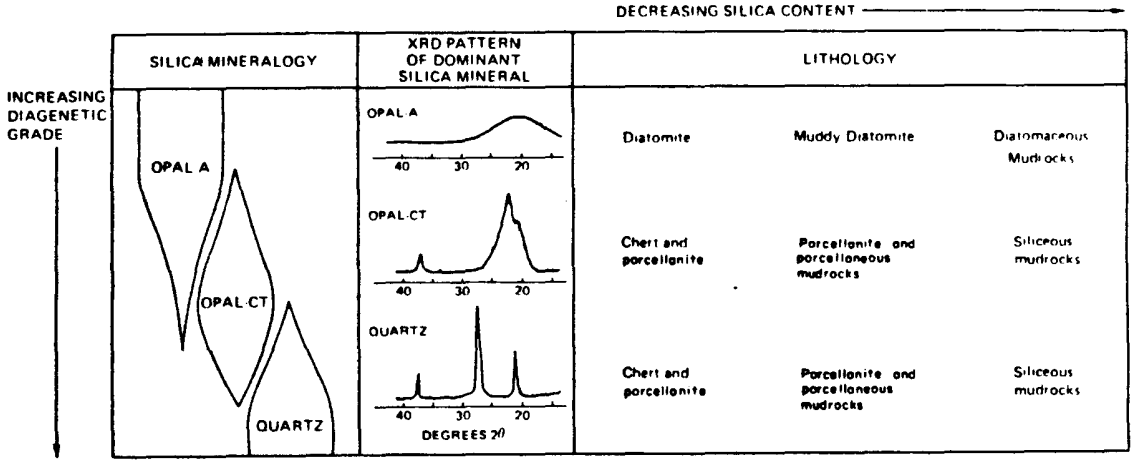


Fig. 1. Generalized classification of siliceous rocks in the Monterey Shale showing the relationship between lithology and dominant silica mineralogy (lithologic terminology after Bramlette, 1946). The term mudrock is used here to represent the full textural suite of fine-grained terrigenous rocks (e.g. mudstone, claystone, shale, etc.).

The temperatures required for this diagenesis are fairly low. The bottom of the opal-CT zone ranges from 38°C to 54°C and the top of this zone from 55°C to 110°C. It was indicated that this diagenetic process is most sensitive to heat and less sensitive to pressure. Further, the transformation of opal-A to opal-CT and of opal-CT to chert is a solution/precipitation process. Within the opal-CT range the X-ray diffraction study done here indicates some decrease in d spacings with increased diagenetic grade. The results of an X-ray diffraction study done on sediments taken from two drill holes in Tenpoku of Northern Hokkaido show a systematic decrease in d spacing with increase burial depth. (Iijima and Tada, 1981).

Iijima and Tada call the transition from biogenetic amorphous silica into opal-CT a dissolution/precipitation process and also states that the ordering of opal-CT is a solid state reaction. The papers by Pisciotto and ~~Imamtada~~ Iijima & Tada rather clearly indicate that there is a diagenetic grade from opal-A to opal-CT to chert with increasing temperature. In a depositional sense this probably represents increase in depth of burial, but could represent proximity to a buried magma heat source.

The term opal-CT, which I have previously said is used in regard to disordered low cristobalite, arises from disorder in the vertical stacking of the hexagonal layers which is for the most part cristobalite stacking, but in some ways resembles tridymite stacking. Wilson, Russell and Tait (1974) report that low cristobalite, previously thought to be disordered cristobalite, might be disordered tridymite stacking with random shifts perpendicular to the c-axis. However, Jones and Segnit (1975) reply that the stacking is indeed cristobalite stacking. Jones and Segnit cite several reasons which are beyond the scope of this paper, however, they cite the results of a differential thermal analysis study (Jones and Segnit, 1971), which clearly shows discontinuities at temperatures appropriate not only for tridymite inversions, but also cristobalite inversions from low temperature to high temperature forms. If only tridymite stacking was present, the temperature discontinuities representing the cristobalite inversion would not be seen in low temperature forms.

According to Frondel (1962) the chemical composition of opal is hydrous silica. Most of the water is non-essential water held by capillary action as a result of very small individual crystallites and is readily lost upon desiccation or by heating. The amount of water ranges up to 20 percent but is commonly between four and nine percent. Frondel also reports the chemical analysis of 100 opal sinters, and says that the impurities which are present in opal include Al_2O_3, Fe_2O_3, CaO, MgO, and alkalies.

Frondel says:

> "The role of these constituents is not well-established, but in many instances, they must be ascribed in part or entirely to admixed clay, coprecipitated gels of $Al_2O_3 \cdot nH_2O$ and $Fe_2O_3 \cdot nH_2O$, and other physical impurities."

Segnit, Stevens & Jones (1965) used differential thermal analysis, thermo gravimetric analysis and infrared analysis and concluded that the major part of the water in opal is held physically by capillary condensation or as hydroxyl groups chemically bonded to the silica surface.

Precious opal is characterized by a play of colors. Although the exact origin of these colors is still problematic, it is thought that it results from the closest packing of small spheres of amorphous silica or possibly spheres of cristobalite which have an approximate diameter in the range of the wavelength of visible light. These close packed spheres are stacked in either hexagonal closest packed arrangement or cubic closed packed stacking arrangement and act to diffract visible light which results in the play of colors. Sanders (1968) discusses in some depth the play of colors in precious opal. In his study an optical diffractometer was used to work out the arrangement of the amorphous spheres within amorphous precious opals. The optical diffractometer is used much like an X-ray diffraction unit and the Bragg equation is used to figure out the manner in which the closest packed layers of amorphous silica are stacked. Stacking may be random, cubic closest packed, or hexagonal closest packed. Sanders describes the ways in which these stacking arrangements affect the appearance of colors. Sanders also discusses the effect of the size of the individual spheres on the displayed color.

Florke, Jones and Segnit (1975) report the synthesis of opal-CT at 50 bars of pressure and temperatures ranging between 150°C to 200°C. The starting material was pure silica and the reaction solutions were two mole percent sodium, potassium, or cesium hydroxide in water. Opal-CT was formed in 6 to 9

days, after which it was replaced by the stable quartz phase at approximately 12 days. They found that crystal habits are similar in both natural opal-CT and in the synthetic opal-CT. They say:

> "The well-known anomalous X-ray pattern of opal-CT may now be understood as being due to the combined action of stacking disorder and the effect of an anisotropic crystallite shape."

Even though the literature includes schematic representations of X-ray diffraction patterns, it is hard to get any real feel for these patterns without actually running some. Thus it was decided to survey the opals that are present in the collection at The Ohio State University to determine if there was a correlation between megascopic appearance and X-ray diffraction patterns. After reading the literature, I expected to be able to predict, in some cases, what kind of patterns I would get based upon the physical appearance of the different types of opals. For instance, when I X-rayed diatomite I was fairly sure that I would get a strictly amorphous pattern, and indeed I did. I was equally sure, however, that I would get a strictly amorphous pattern from the precious opals that were X-rayed, but I did not. So, I intend to describe each of the opals that was selected for this study and report the type of pattern that was found. I will also, take an overview of these patterns trying to recognize the significance of any trends in d spacing, and/or peak shape and/or intensity of the peaks, and discuss such trends, and draw whatever conclusions become apparent.

EXPERIMENTAL PROCEDURE

Representative specimens of opal were selected from the mineralogy collection at The Ohio State University. To prepare each specimen for powder methods X-ray analysis, a small portion was broken away by means of gently tapping a corner or sharp edge of the specimen with the rounded edge of a pair of pliers. Most specimens are brittle and small fragments were chipped directly into a mortar where they were ground with a pestle into a fine powder having the consistency of flour. Care was taken to obtain fragments exclusively from the desired portion of a specimen. The physical appearance of the specimen was described, noting which portion of the non-uniform specimens was sampled.

A small amount of powdered sample, sufficient to cover a standard glass slide with a thin film (when mixed with acetone), was transferred to a glass slide covered with a generous amount of acetone. The powder and acetone were thoroughly mixed and spread evenly on the slide. Mixing was stopped just prior to the total evaporation of the acetone. With practice the result was an even smear mount. The smear mounts were then X-rayed from $4°2\theta$ to $60°2\theta$ using CuK radiation with a theta-compensating slit and a graphite monochromator at a scan speed of $1°2\theta$ per minute, a chart speed of 30 in/hr, and a setting 35KV/15ma and 500 cps. The smear mounts and any excess powdered samples were labled and kept for future study.

DATA AND RESULTS

The following are physical descriptions of the specimens selected for this study.

#1) Specimen 7305* is a translucent light cream color common opal with a waxy luster and conchoidal fracture.
Locality: Virgin Valley Humboldt Co., Nevada

*These numbers refer to The Ohio State University Mineralogy Museum Catalog.

#2) This specimen is a translucent milky white chalcedony with a waxy luster and sub-conchoidal fracture.
Locality: unknown

#3) Specimen 4326 is an opaque milk white common opal with a vitreous luster and conchoidal fracture. There were small patches of transparent precious opal on this specimen but the sample was taken from the common opal portion.
Locality: Guanojuato, Mexico

#4) This specimen is an opaque light tan common opal with a dull waxy luster and sub-conchoidal fracture. One side of the specimen has a drusy coating of white chalcedony which was not included in the sample.
Locality: Yuma Co., Arizona

#5) Specimen 8697 is colorless transparent globular hyalite opal which displays conchoidal fracture.
Locality: Czernowitza, Hungary

#6) Specimen 9912 is a very friable white very thin bedded rectangle of diatomite.
Locality: Zampoe, California

#7) Specimen 3888 is a porous white stalactitic geyserite.
Locality: Yellowstone Park, Wyoming

#8) Specimen #212 is an opaque black semi-precious opal with a vitreous luster and pronounced conchoidal fractures.
Locality: unknown

#9) Specimen 6423 is a transparent to opaque precious opal which is a psuedomorph after wood. The transparent portion shows a play of colors, blue, green and orange. The sample was taken from the transparent portion.
Locality: Nevada

#10) Specimen 1396 is a lavender opaque common opal with a sub-vitreous luster and sub-conchoidal fracture.
Locality: Near Boise City, Idaho

#11) Specimen 8965 is a red transparent common fire opal with a vitreous luster and conchoidal fracture.
Locality: Guerataro, Mexico

#12) This specimen is a light tan chert nodule with white waxy opal looking material in the center. The sample was taken from the white waxy central portion.
Locality: Temple Hill, Manti, Utah

#13) Specimen 6421 is a 1/4 inch vein of transparent precious opal in a matrix of dark gray pebble conglomerate. The sample was taken from the precious portion which showed internal colors of red, orange, yellow, green and some blue.
Locality: Nevada

#14) This specimen is a beige common with a waxy luster and displays conchoidal fracture. There is a white clay layer on one side of the specimen which was not included in the sample.
Locality: unknown

#15) This specimen is a jet black obsidian containing spheres of cristobalite which were sampled.
Locality: California

#16) This specimen is a honey colored translucent common opal with a vitreous luster and pronounced conchoidal fracture.
Locality: unknown

#17) This specimen is a banded purple to lavender translucent common opal with vitreous luster and uneven fracture.
Locality: Millard Co., Utah

#18) Specimen 8709 is a red to dirty brown translucent petrified wood with a waxy luster.
Locality: unknown

#19) This specimen is a banded beige to tan opaque common opal with subvitreous luster conchoidal fracture.
Locality: unknown

#20) This specimen is a red transparent semi-precious fire opal with a vitreous luster and conchoidal fracture, but does not display a true fire.
Locality: Virgin Valley Humboldt Co., Nevada

#21) This specimen is a light tan opaque common opal with a waxy luster and conchoidal fracture. There is a white clay layer on one side of the specimen which was not included in the sample.
Locality: Virgin Valley Humboldt Co., Nevada

#22) This specimen is a banded honey brown opaque common wood opal with a waxy luster and sub-conchoidal fracture.
Locality: Meridian, Idaho

#23) This specimen is a variegated red to yellow brown and white petrified wood with a waxy luster and sub-conchoidal fracture.
Locality: Arizona

#24) This specimen is a green opaque common opal with waxy luster and conchoidal fracture, half of this specimen was red opaque jasper which was not included in the sample.
Locality: unknown

#25) This specimen is a white translucent to opaque porous fulgurite formed by a downed power line.
Locality: Ft. Leonard Wood, Missouri

#26) Specimen 8710 is an opaque to translucent precious opal with a vitreous luster and conchoidal fracture. The internal colors range from red to yellow and green to blue.
Locality: Australia

Table I is a tabulation of the 2θ values of ∝cristobalite and ∝tridymite peaks for the specimens X-rayed for this study. In all cases the 2θ values between 21.4 and 22.4 were the most intense, those between 20.35 and 20.70 had the next highest intensity, and peaks between 35.30 and 36.00 were least intense. The patterns are arranged in order of most crystalline to least.

TABLE I

Two-theta values for selected peaks on X-ray diffraction patterns from opals taken with CuK radiation.

SAMPLE	2θ VALUES		
CRIST			
#15		21.90	36.00
OPAL-C			
#9	21.75 →	35.90 →	
#13		21.60	35.70
#8		21.70	35.80
OPAL-CT			
#10	20.70	21.65	35.90
#3	20.35	21.50	35.70
#19	20.70	21.60	35.80
#4	20.60	21.60	35.78
#11	20.65	21.60	35.75
#1	20.60	21.50	35.65
#24	20.65	21.70	35.80
#16	20.40	21.40	35.60
#20	20.60	21.55	35.80
#22	20.60	21.60	35.98
#21	20.60	21.55	35.60
#14	20.50	21.60	35.95
OPAL-A			
#17	20.60	21.80	35.30
#5		22.4	
#7	20.7	23.2	
#6		21.9	
#26	20.7	22.1	
#25		22.4	

Samples #2, 12, 18 and 23 are quartz.

The following is a list of x-ray patterns from The University of Illinois clay mineral collection. These clay mineral x-ray patterns also contain ∝cristobalite. The clays and other phases present include smectites, kaolinite, illite, mica, and others.

#53 Sample 115B Cherry Lease, Texas (4/4/72)
Smectite, ∝cristobalite, and others.

#51 U of I #32 Ponza, Italy (4/4/72)
Smectite, ∝cristobalite, and others

#58 B92 Africa (4/8/72)
Smectite, ∝cristobalite, and others

#63 Sample 202B Ponza, Italy (4/20/72)
Smectite, ∝cristobalite, and others

#62 Sample 206 Japan (4/1/1)
Smectite, ∝cristobalite, and others

#66 Sample 210B Australia (4/21/72)
cristobalite and others

#75 Sample 72B Creede, Colorado (5/2/72)
Smectite, ∝cristobalite, and others

#79 Sample 211 Ivory Ponza Bentonite (1/72)
Smectite, ∝cristobalite, and others

#86 102 F.E. Dry Branch, Georgia (5/13/72)
Smectite, ∝cristobalite, and others

#96 79 Fullers Earth, San Antonio, Texas (6/14/72)
Smectite, ∝cristobalite, and others

#82 Fullers Earth (12/1/72)
Smectite, ∝cristobalite, quartz, and others

#100 264-E (11/9/72)
Kaolinite, ∝cristobalite, quartz, and others

#101 264-A (11/4/72)
Kaolinite, ∝cristobalite, and others

#102 264-B (12/6/72)
Kaolinite, ∝cristobalite, quartz, and others

#95 82 Fullers Earth, Macon, Georgia (6/14/72)
Smectite, ∝cristobalite, and others

#39 U of I Fullers Earth, Ocala, Florida (3/10/72)
Smectite, ∝cristobalite, ∝tridymite, quartz, and others

#82 107B Mowry, South Dakota (5/12/72)
Smectite, mica, ∝cristobalite, and others.

Table II is a tabulation of the ∝cristobalite peaks of the patterns from The University of Illinois. The intensities of the peaks are in the same order as Table I.

TABLE II

Two-theta values for cristobalite/tridymite peaks from X-ray diffraction patterns of clay minerals from the University of Illinois clay mineral collection taken with CuK-radiation.

SAMPLE	2θ VALUES		
#53		21.6	36.00
#51		21.8	36.00
#58		21.8	36.00
#63		21.8	36.00
#62		21.9	36.10
#66		21.9	36.00
#75		21.9	35.90
#79		21.7	35.90
#86		21.6	36.00
#96		21.8	36.00
#82		21.6	35.80
#100		21.9	36.00
#101		22.0	36.50
#102		22.0	36.05
#95		21.6	35.5
#39	20.6	21.7	35.75
#82		21.9	36.1

Figure 1

X-ray diffraction patterns of Opal-A samples taken with CuK radiation of (a) sample #17, (b) sample #26, and (c) sample #25

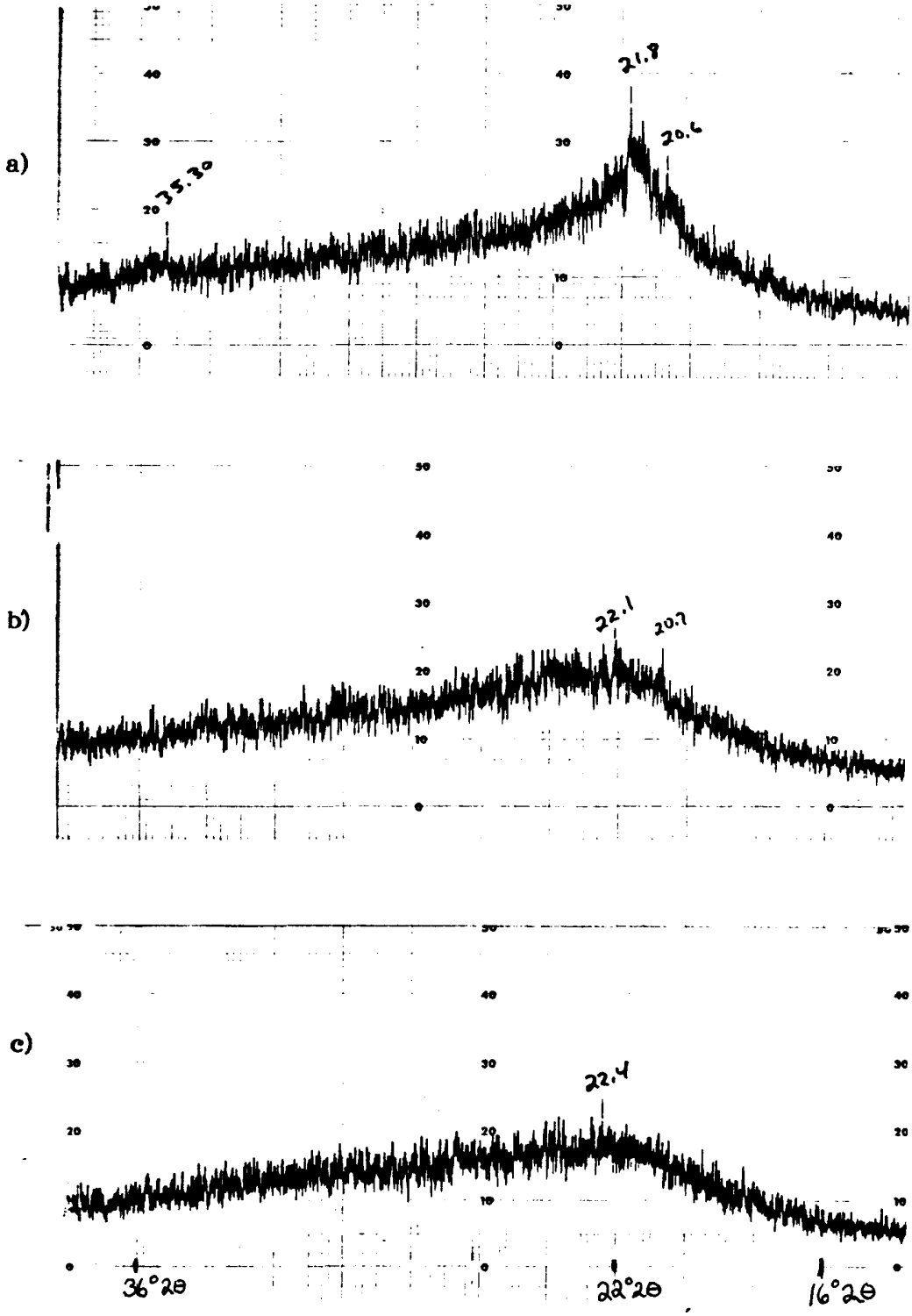


Figure 2

X-ray diffraction pattern of Opal-CT samples taken with CuK radiation of (a) sample #3, (b) sample #11, and (c) sample #21

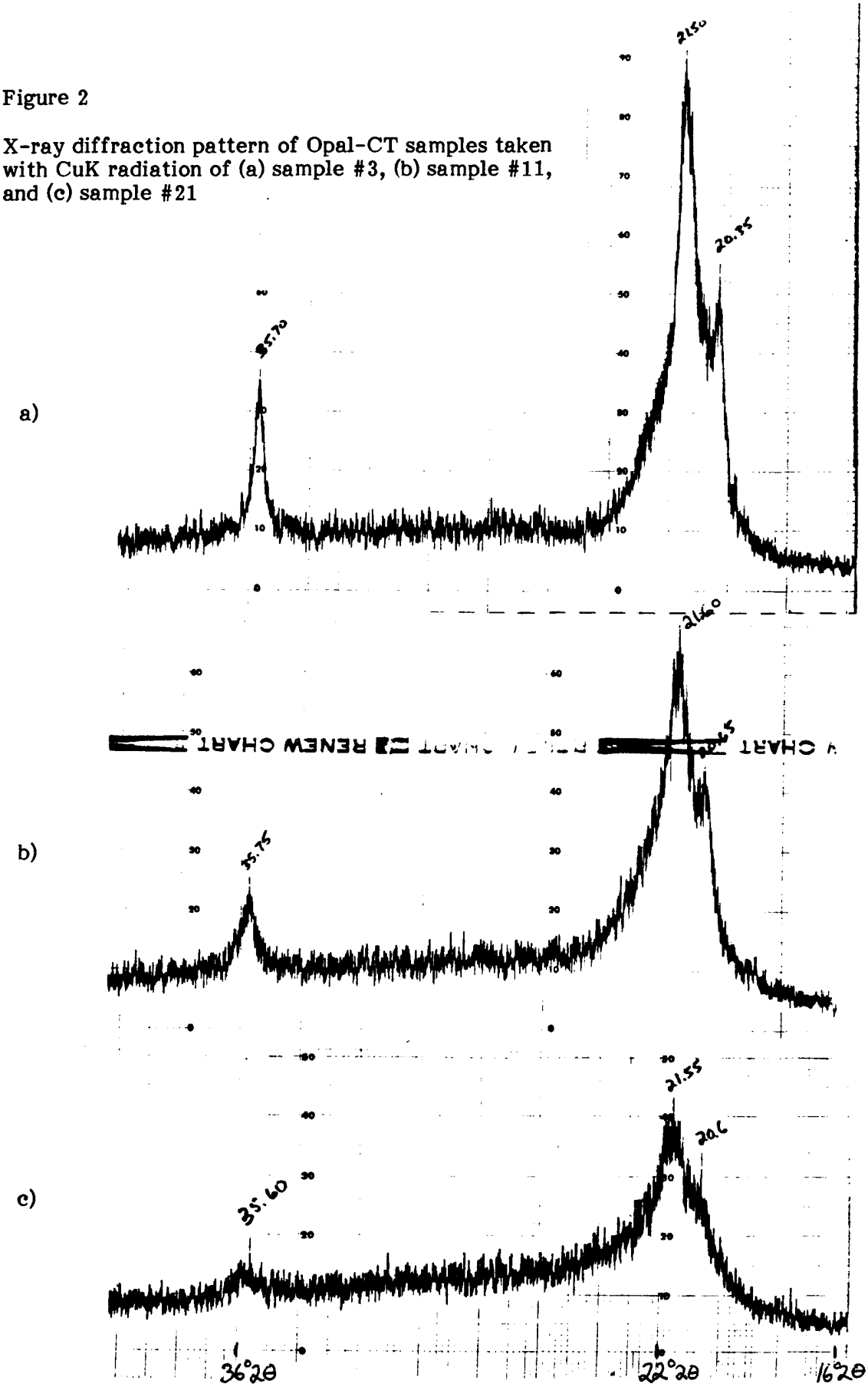


Figure 3

X-ray diffraction patterns of Opal-C samples taken with CuK radiation of (a) sample #9, (b) sample #13, and (c) sample #8

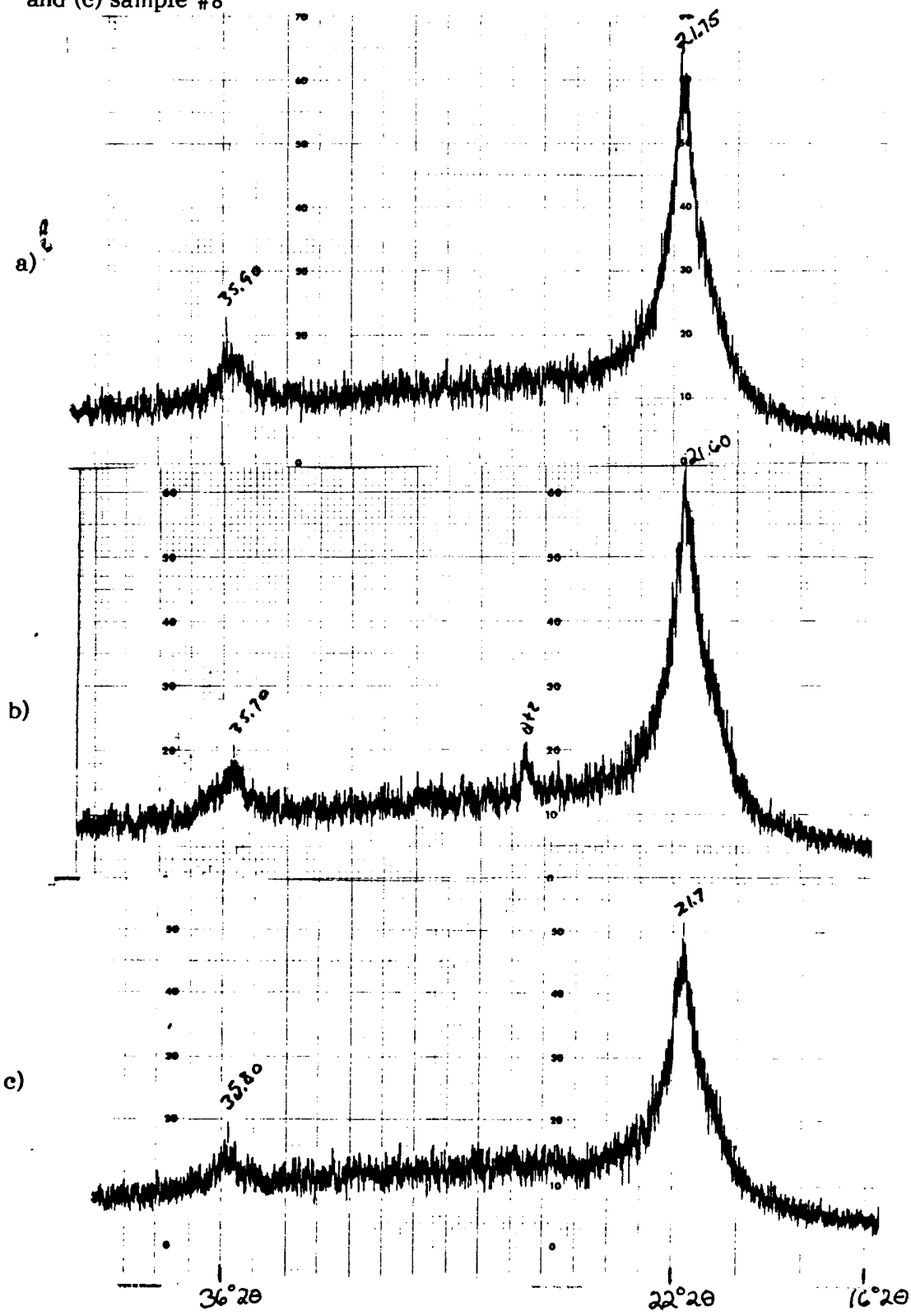


Figure 4 and Figure 5

X-ray diffraction patterns taken with CuK:
Figure 4 of ∝cristobalite and Figure 5
of a clay sample which contained quartz,
∝cristobalite, ∝tridymite, and smectite.

Fig. 4

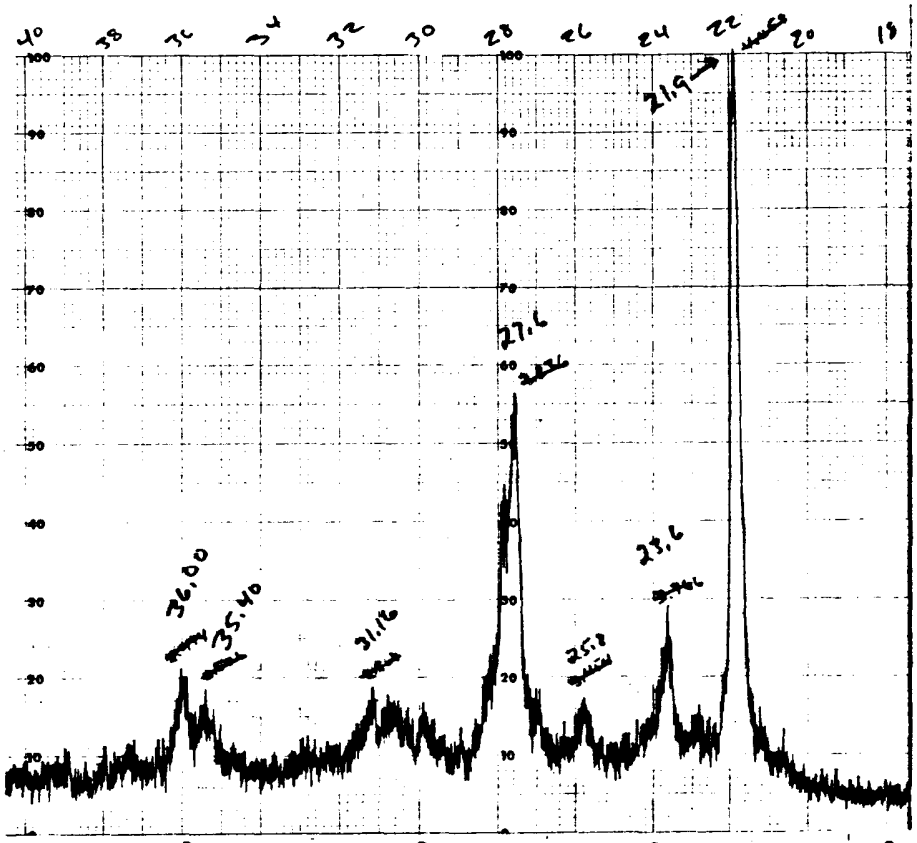
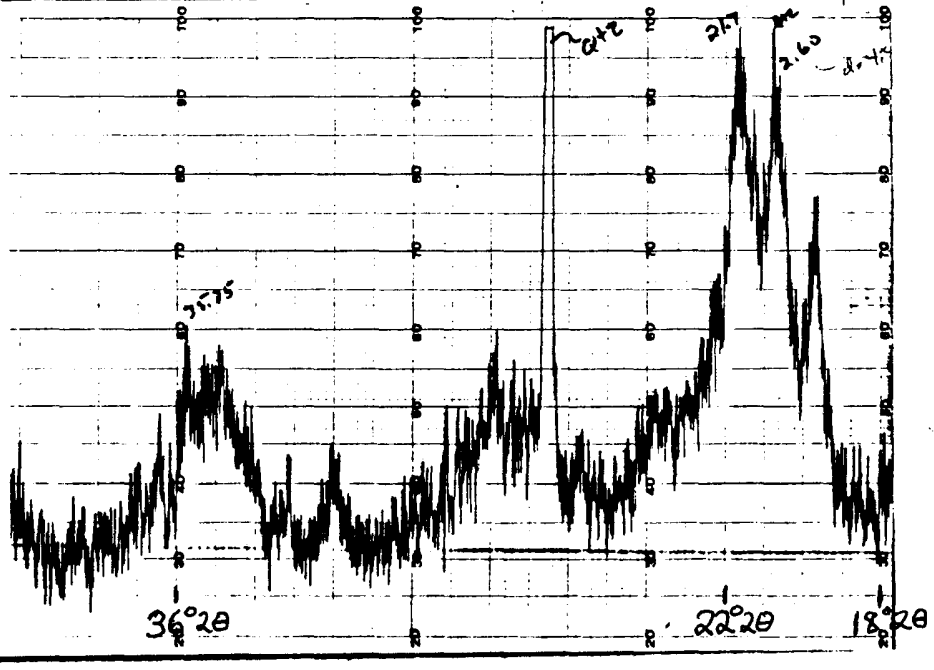


Fig. 5



DISCUSSION OF RESULTS

The X-ray patterns of opal specimens (#1-#26) taken in this study display the characteristics reported by Jones and Segnit (1971), from opal-A through opal-C. Since the specimens were selected on the basis of their physical appearance it is understandable that several specimens would prove to be chalcedony (i.e. quartz having small crystallite sizes). Specimens #2, #12, #18, and #23 were chalcedony. Specimen #15 was X-rayed to obtain an αcristobalite pattern (Fig. 4). Specimen #25 was a fulgurite which is fused silica and it is included with the opal-A patterns (Fig. 1).

Figure 1 shows two opal-A patterns and one of fused silica. These patterns have a single low intensity very broad peak which crests around 22°2θ. This indicates the presence of an amorphous or nearly amorphous material. The patterns of Fig. 1 are arranged with least ordered at the bottom. In pattern #17 three poorly defined peaks are shown at the appropriate positions characteristic of opal-CT. Opal-CT is characterized by an αcristobalite peak at about 21.7°2θ which is the most intense peak. This peak is modified and flanked by a second peak at about 20.6°2θ which often appears as a shoulder on the primary peak. This shoulder is attributed to αtridymite and indicates some tridymite stacking in opal-CT. A third peak at around 35.8°2θ is an αcristobalite peak.

The patterns in Figure 2 are opal-CT patterns. They were selected as representative patterns from least ordered to most ordered opal-CT. When all of the opal-CT patterns in this study were laid out the sharpness and the intensity of the peaks show a continual gradation which suggest a continuous variation in crystallinity and/or crystallite size. Jones and Segnit (1971) label a pattern which has a tridymite shoulder on the primary cristobalite peak as

opal-C. The question arises at what point of ordering does one call opal-CT opal-C.

Figure 3 shows the patterns which I have called opal-C. The distinction I made between opal-CT and opal-C is the absence of the tridymite shoulder. The primary cristobalite peak in these patterns has a narrower base indicating larger individual crystallite size and a greater degree of crystallinity. The lack of the tridymite shoulder provides a readily discernible division between opal-CT and opal-C.

Figure 4 shows a pattern of ∝cristobalite which clearly indicates the difference between ∝cristobalite and the opal patterns. The ∝cristobalite pattern shows very sharp peaks with narrow bases while opals' peaks are more broad based and are not as sharp or as intense. Opal-CT and opal-C show only the two most intense peaks of ∝cristobalite and these peaks occur at slightly lower 2θ values.

Frondel (1962) refers to opal as a variety of ∝cristobalite in the same way chalcedony is a variety of quartz. Jones and Segnit (1971) take exception to this. They point out that chalcedony is structurally identical to quartz while opal groups are structurally distinct from each other and from ∝cristobalite. I believe my study supports the position of Jones and Segnit.

Figure 5 shows pattern #39; one of the clay patterns from the University of Illinois which contained ∝cristobalite. This particular pattern was included because it also has an ∝tridymite peak at 20.6°2θ of nearly equal intensity to the ∝cristobalite peak at 21.7°2θ. This was the only pattern to show this feature.

The patterns which were placed into the opal-C category are all precious opal. The precious opals in this study X-rayed as either opal-A or opal-C. This may result from the presence of a particular partical size which produces a play of colors. If an opal is to be both crystalline and precious, then the crystallites must be large enough to interact with visible light.

This large crystallite size may only be attained by opals which are well ordered, such as opal-C. This study is too limited to speak to this problem. If crystallite size in opal-C is related to a play of colors, a future study might investigate this possible relationship. Since the crystallite size affects the width of peaks the relationship between effective X-ray crystal size and crystallite size might be investigated.

CONCLUSION

Opals are divided into three structural groups based on their X-ray diffraction patterns and are termed opal-A, opal-CT and opal-C. The boundary between opal-CT and opal-C should be made on the basis of the presence or absence of a trydimite shoulder on the primary ∝cristobalite peak. No relationship bewteen d spacing and opal type or apparent X-ray crystallinity are recognizable from this limited study, although such a relationship has been reported (Pisciotto, 1981 ; Iijima and Tada 1981) and d-spacing variations have been correlated with diagenetic trends by these authors.

On the basis of this study no correlations ~~between~~ with the physical appearance of the hand specimens can be made. However, Jones and Segnit (1971) state that hyalite; most precious opal and opaline silica are opal-A while most common opals are opal-CT. All of the opals in the category opal-CT that I X-rayed were common opals. All opal-C opals in this study were precious opal. The opal-A category consisted of hyalite, opaline silica, precious opal and common opal. These results are consistent with Jones and Segnit (1971), but are not sufficient to draw any further conclusions. Chalcedony can be differentiated from opal by specific gravity, hardness, and a quartz X-ray diffraction pattern.

LIST OF REFERENCES

Dollase, W.A., 1965, Reinvestigation of the structure of low cristobalite, Z. Kristallogr., vol 121, pp 369-377

Frondel, C., 1962, Dana's System of Mineralogy, vol 3, Wiley, New York

Florke, O.W., Jones, J.B., and Segnit, E.R., 1975, Opal-CT Crystals, Neues Jb. Miner. Mh., vol 8, pp 369-377

Hurlbut, Cornelius S., 1971, Dana's Manual of Mineralogy, Wiley, New York

Iijima, Azuma and Tada, Rynji, 1981, Silica diagenesis of Neogene diatomaceous and volcaniclastic sediments in northern Japan, Sedimentology, vol 28, pp 185-200

Jones, J.B., 1966, Opal Genesis, Nature, vol 210, pp 1353-1354

Jones, J.B. and Segnit, E.R., 1971, The Nature of Opal. I. Nomenclature and constituent Phases, J. Geol. Soc. Australia, vol 18 (Pt. 1), pp 57-68

Jones, J.B. and Segnit, E.R., 1972, Genesis of Cristobalite and Tridymite at low Temperatures, J. Geol. Soc. Australia, vol 18 (Pt. 4), pp 419-422

Jones, J.B. and Segnit, E.R., 1975, Nomenclature and the Structure of Natural Disordered (opaline) Silica, Contrib. Mineral. Petrol., vol 51, pp 231-234

Levin, I. and Ott, Emil, 1933, X-ray Study of Opals, Silica Glass and Silica Gel, Z. Kristallogr., vol 85, pp 305-318

Oehler, J.H., 1973, Tridymite-like Crystals in Cristobalitic "Cherts", Natural Physical Science, vol 241, pp 64-65

Pisciotto, Kenneth A., 1981, Diagenetic trends in the siliceous facies of the Monterey Shale in the Santa Maria region, California, Sedimentology, vol 28, pp 547-571

Sanders, J.V. and Segnit, E.R., 1964, The Structure of Opal, Nature, vol 204, pp 990-991

Sanders, J.V., 1964, Colour of Precious Opal, Nature, vol 204, pp 1151-1155

Sanders, J.V., 1968, Diffraction of Light by Opals, Acta. Crystallogr., vol A24, pp 427-434

Segnit, E.R., Stevens, T.J., and Jones, J.B., 1965, The Role of Water in Opal, J. Geol. Soc. Australia, vol 12, pp 211-226

Wilson, M.J., Russell, J.D., and Tait, J.M., 1974, A New Interpretation of the Structure of Disordered α-Cristobalite, Contrib. Mineral. Petrol., vol 47, pp 1-6

Zoltai, Tibor, and Buerger, M.J., 1960, The relative energies of rings of tetrahedra, Z. Kristallogr., vol 114, pp 1-8